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Direct Electron-Pair Production by High Energy Heavy Charged Particles

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1. Introduction.

Direct electron-pair production by high energy nuclei has been recognized as an important physical process occuring in observation of high energy cosmic ray nuclei. Direct electron pair production via virtual photons by moving charged particles is a unique electro-magnetic process having a substantial dependence on energy ($\propto \ln^{3-4} E$). Most electro-magnetic processes, including transition radiation, cease to be sensitive to the incident energy above 10 TeV/AMU. Few experimental studies of direct pairs have been made in the past, though their influence has been recognized in continuously increasing signals in ionization and Cerenkov counters at energies expected for saturation, and direct pairs have been explicitly detected in emulsion chambers along tracks of high energy heavy nuclei. Thus, it is expected, that upon establishment of cross section and detection efficiency of this process, it may provide a new energy measuring technique above 10 TeV/AMU.

Under the grant (NAG8-065), the UAH team has performed three accelerator exposures of emulsion chambers designed for measurements of direct electron-pairs. Fig. 2 illustrates four types of chambers designed and exposed. These accelerator experiments were made at Lawrence Berkeley Laboratory, University of California, and at the European Center for Nuclear Research (CERN), Geneva, Switzerland. The former was done in 1985 and the latter were done in October-November, 1986 with oxygen beams at

60 and 200 GeV/AMU, and in September 1987, with sulphur beams at 200 GeV/AMU.

Measurements of electron-pairs were performed in emulsions with microscopes in the Cosmic Ray Laboratory at UAH. Total track length of about 56m were scanned under the microscope with a magnification of 1200x so that scanning efficiency is optimized. Measurements of the delta-ray range spectrum were also performed for much shorter track lengths, but with sufficiently large statistics in the number of measured delta-rays.

This paper reports the design of the emulsion chambers, accelerator experiments, microscope measurements, data, and related considerations for future improvements of the measurements, and for possible applications to high energy cosmic ray experiments.

2. Objectives and Design of Emulsion Chambers.

The objectives of the investigation were to provide the fundamental cross-section data in emulsion stacks to find the best-fit theoretical model, and to provide a calibration of measurements of direct electron-pairs in emulsion chamber configurations. Four different configurations of the emulsion chamber were used, and details of which are shown in Fig.2 and Table 1. The emulsion stack, (D) in Fig. 2, was the basic design for the cross-section investigation, while emulsion chamber configurations, (A), (B), and (C), in Fig. 2, were prepared for calibrations of the detector for future cosmic ray experiments. The latter three configurations will let cosmic ray emulsion chamber experiments be calibrated at three fundamental dip-

angles, namely 0°, 30°, 45° measured from the normal axis to the plate. The cross section measurements were performed in emulsions of the design (D), for which biases and contaminations were minimal in acclerator experiments.

The dimensions of emulsion plates used in accelerator experiments were standardized to 8 cm x 12 cm in surface area. Thickness of each plate of the design (D) was from 770 microns to 1500 microns, as shown in Table 2, depending on the base substrate (one type uses polystyrene film of 70 micron thick, and another type uses plexiglass plate of 800 micron thick). The design (A), (B), and (C), use multiple emulsion plate-lead plate clusters, simulating the actual emulsion chamber configurations adopted in cosmic ray experiments. The plates have a standard surface area of 8 cm x 12 cm, and thickness of 170 to 1000 microns, depending on base substrates.

Nuclear emulsions were procured in gel. form from Fuji Film Co., with which emulsion plates were produced by us at the emulsion facility of the Fermi National Accelerator Laboratory (FNAL), and CERN, within one month before the accelerator experiments.

Each chamber was constructed with a box-container that is made of opaque black plexi-glass, measuring 10 cm x 14 cm x 20 cm. Twenty blocks of the emulsion chambers (Table 1) using about 1.5 litres of nuclear emulsions (dry) were prepared for each experiment.

3. Accelerator Exposures.

3-1. A Low Energy Calibration Experiment

For cross section measurements at low energy, an experiment was performed with nuclear emulsion stacks (design (D)) by using the 1.8 GeV/AMU ^{56}Fe beam of the Bevalac accelerator, Lawrence Berkeley Laboratory, University of California. One person from UAH (John C. Gregory) travelled to Berkeley to assist with this experiment.

3-2. High Energy Calibration Experiments

Experiments at high energies were performed at the H-3 beam line of the West Area at the SPS accelerator, European Center for Nuclear Research, Geneva, Switzerland. One person from UAH (Y. Takahashi) travelled to Geneva to assist with these experiments. Beams planned were ^{16}O and 200 GeV/AMU, and ^{32}S at 60 and 200 GeV/AMU. Exposures with ^{16}O beams were achieved in November (200 GeV/AMU) and December (60 GeV/AMU), 1986, while that with ^{32}S were made in October 1987, at only 200 GeV/AMU. ^{32}S at 60 GeV/AMU experiments were indefinitely postponed due to the change of the entire ion-experiment plan by the CERN SPS Committee, but may become possible after 1990.

Emulsions were developed within a few months after the exposure to the beams. Processing facilities at the CERN EP Division, and at the Space Science Laboratory, NASA/MSFC were used for development and chemical fixing of nuclear emulsions for all the experiments.

4. Scanning and Measurements in Emulsions with Microscopes

Emulsion plates have been scanned with microscopes at the UAH Cosmic Ray Laboratory. Line scanning along the track was adopted. Each track of a beam nucleus was traced from the position in emulsions at the entrance until the end of the track. The end of the track is defined when the track encountered either of the following:

1. The primary track makes a nuclear interaction,
2. The primary track passes out of the plate.

The typical track length in a plate for each track so defined is 6-8 cm, if it does not make a nuclear interaction. This length of track for tracing is essentially pre-determined by the design, as the beams are exposed to plates parallel to the shorter length of the plate (8 cm). Scanning of electron-pairs along the track of a beam nuclei was made by a magnification of 1200 = (100 x 10 x 1.2) with a Nikon microscope. The highest magnification was adopted to provide the best possible efficiency in detecting produced electron-pairs, which otherwise can be occasionally missed due to the thin track image of produced electrons.

The scanning was made for a track over the focusing depths +/- 20-30 microns from the position of the primary tracks. Scanning speed was about 3 cm per hour. In the second scanning, that of 1 cm/hour was adopted to check the effect of scanning speed on the detection efficiency.

An electron pair was identified when a pair of tracks emerge from a point in the primary nucleus track. The "point" vertex was defined when the distance of the merging points of two electron tracks with the primary track were separated by less than 2 microns [criterion 1]. This convention cannot be very strict or precisely reliable when at least one of a pair of tracks is emitted with very small angle (less than 0.01 radian). The uncertainty of the "point vertex" for these pairs loosens the effectiveness of the set criterion of less than 2 micron separation. Hence, the data would be subject to contamination of chance coincidence of long-range delta-rays, which is evaluated later by using the delta-ray range spectrum.

An additional set of criteria for identification of an direct electron-pair is applied simultaneously with regard to the apparent track length of electrons. To be judged as the candidate pair, at least one track has to have an obvious range (Ro) exceeding one field of view (FOV) which corresponds to Ro=200 microns [criterion 2].

Furthermore, the second track (with shorter-range) must satisfy another requirement of having at least Rmin=100 microns in "apparent" track length [criterion 3]. Here, "apparent" track length means the range visible at the field of view without tracing the individual tracks to the end of its range. The electron (positron) energies corresponding to R $\geq$ 100 microns and 200 microns are $\geq$ 140 (150) KeV and $\geq$ 215 (225) KeV, respec-

tively. We note here that these electron (positron) energies are the minimum estimate (smaller) than the true value by about 100 KeV, because the actual tracks at energies below 100 KeV suffer large-angle multiple scattering at lower energies and their range-measurements give shorter range than the actual one. Nevertheless, uncertainties in this conversion does not affect the cross section analysis very much, because the low energy-transfer cross section is negligibly small at the primary energy in concern.

An angular criterion is also applied. The angle of the largest angle of two tracks (Theta (max)) should be within 45° measured from the direction of the primary track [criterion 4]. This angular cut-off in measurements will reduce the number of detected events, however, it is not more than 1% of the cross section at the primary energy in concern.

All the obtained cross-section data are plotted in Fig. 3 in units of Yield (No. of Pairs per 3 cm of Track Length) in emulsion, and compared with various calculations with differenct approximations.

Table IV summarizes the data for all measurements. The last column that is marked with (*) indicates the results of re-scanning with the slow scanning speed of 3 cm/hour may be inefficient by ~30%. However, for these slow measurements, we relaxed the [criterion 3] from Rmin = 100 microns to 50 microns,

TABLE IV

Plate Name	2B12	4D-1-1-3	4D-2-1	4H2-11	4H2-7	4H2-7*
Primary	^{56}Fe	^{16}O	^{16}O	^{32}S	^{32}S	^{32}S
Energy (GeV/AMU)	1.8	200	60	200	200	200
Length (m) scanned	0.964	29.59	9.78	8.74	4.63	2.28
Number of pairs	27	270	46	208	104	74
Yield (No./m)	28.0	9.12	4.86	23.80	22.46	32.46
(+/- error)	5.0	0.55	0.72	1.65	2.20	3.77

and also [criterion 4] from Theta (max) = 45° to 60°, which would include more contaminants by chance coincidence of long-range delta-rays, and care for this contaminant must be taken before defining the inefficiency factor for the data in the Table IV.

5. Data of Delta-Ray Range Spectrum and Its Influence on the Pair Data.

The transversal range spectrum of delta-rays is obtained for all accelerator-exposed emulsions. Here the transversal range (R_T) is defined by the range perpendicular to the direction of the primary nucleus track. This convention of the transversal range is useful for delta-rays with momentum less than a few hundred KeV, because they are mostly originally produced transversally, and do not have a sharp peak at the small emisison angles, while very high energy delta-rays would cause a large difference in average ranges at a fixed energy between R_T and the total range R.

All the data are shown in Figure 4, where charge scaling law ($\propto Z^2$) is satisfactorily indicated between high energy ^{16}O and ^{32}S nuclei. However, a significant difference in R_T spectrum is observed between high and low energy data. The cause of this difference is unclear, but an effect of secondary electron tracks due to transition radiation is discussed, and which will be reported elsewhere.

Here we only utilize these data to evaluate possible contaminants of delta-ray chance coincidence to the electron pair

data in the slow-scanning mode. We take the sulphur data for discussion. The minimum ranges of tracks of a pair in criteria 2 and 3 are 200 and 50(100) microns. Corresponding yield of delta rays are 90 (35) and 12 per cm. Using these values, maximum expected contaminants due to delta-ray coincidence per 1 meter within 2 micron separation and within 60°/180° = 7.2 pairs/m. This value is roughly comparable to the difference between yields at two different scanning rates. Thus, it is not necessarily correct to adopt 70% efficiency for the data obtained by the fast scanning mode (3 cm/hour). To define a more reliable detection efficiency further studies and examinations of delta-ray contaminants are required, with detailed measurement of the angular distribution of delta-rays around the cut-off ranges in electron-pair measurements.

6. Conclusions.

Considering the upper bound for corrections of detection inefficiency (30%), the present investigations suggest that the overall cross section for production of electron pairs is systematically smaller than most available approximate theoretical predictions. Whether it is due to inappropriate theoretical treatments or due to some other detection problems is not clear from this study. Further studies with high energy nuclei with different energies and nuclear species are highly recommended to clarify the curious results encountered by the present investigations.

7. Acknowledgements.

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TABLE I. EMULSION CHAMBERS

CHAMBER DESIGNS

NAME	ENERGY	BEAM INTENSITY
4A - 1, 2	200 A GeV	$3 \times 10^3/cm^2$
4A - 3, 4	60 A GeV	
4B - 1, 2	200 A GeV	2×10^3
4B - 3, 4	60 A GeV	2×10^3
4C - 1, 2	200 A GeV	2×10^3
4C - 3, 4	60 A GeV	2×10^3
4D - 1	200 A GeV	2×10^3
4D - 2	50 A GeV	2×10^3
4D - 3	TBD	TBD

TABLE 2. NUCLEAR EMULSION PLATES

	TYPE	BASE(μm)	EMULSION SIDING	THICKNESS(μm) FRONT/REAR	NUMBER OF PLATES/CHAMBER	TOTAL NUMBER OF PLATES (x4)	PLATE SIZE (cm)
4A	P1	800	7B/7B	50/50	20	80	12 x 11
	P2	800	7B/7B	300/300	4	16	12 x 11
	P3	800	7B/6B	300/300	2	8	12 x 11
4B	P1	800	7B/7B	50/50	20	80	12 x 9
	P2	800	7B/7B	300/300	5	16	12 x 9
	P3	800	7B/6B	300/300	2	8	12 x 9
4C	P1	800	7B/7B	50/50	20	80	12 x 8
	P2	800	7B/7B	300/300	5	16	12 x 8
	P3	800	7B/6B	300/300	2	8	12 x 8
4D	P4 (4D1 & 4D3)	800	7B/7B	500/500	40	100	12 x 8
	4D2	800	7B/7B	500/500	20		

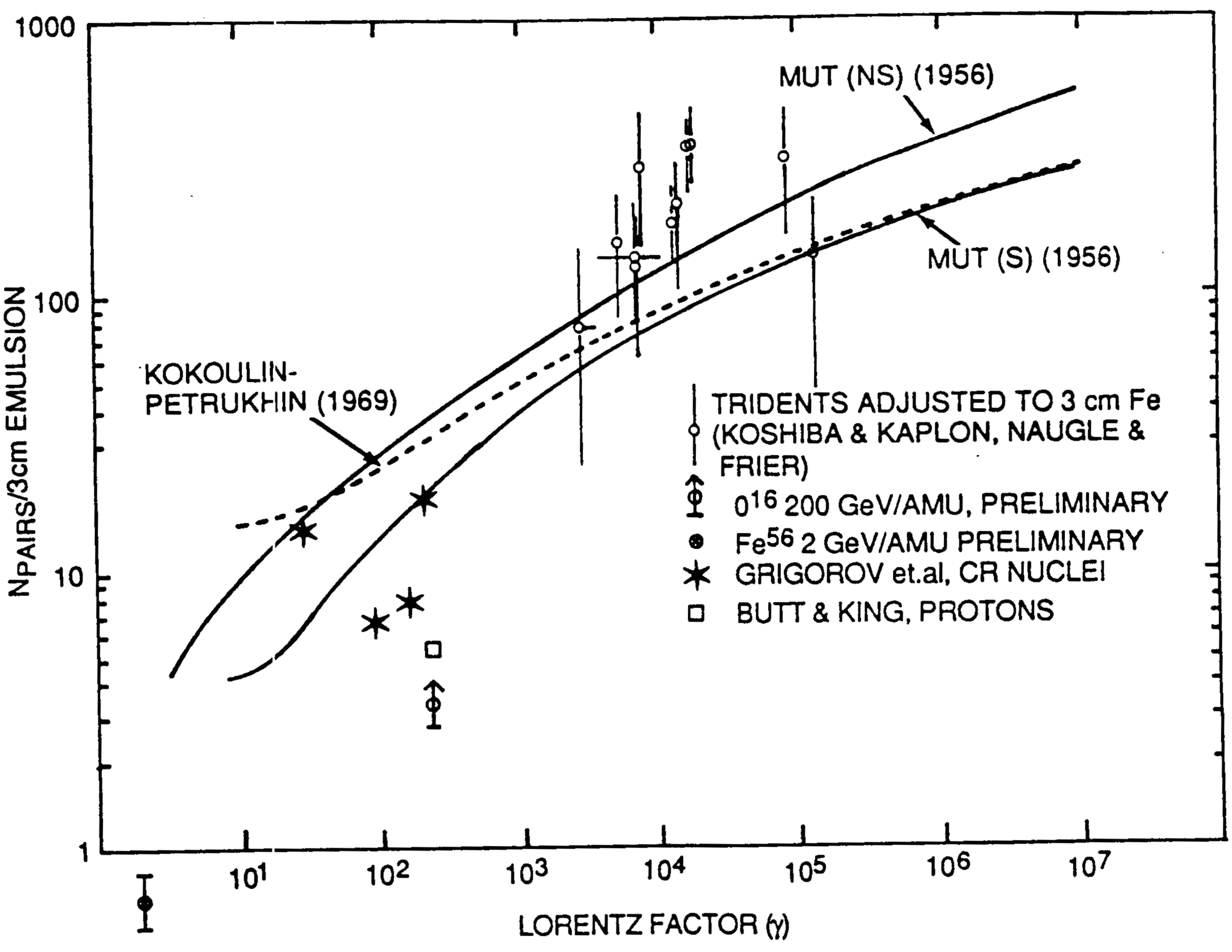
TABLE 3. TABLE OF BLOCKS

BEAM INTENSITY (200 GeV)

EXPERIMENT	CHAMBER	FLUENCE/cm^2
EMU04		
	4A1	
	4A2	
	4B1	
	4B2	$\sim 2 \times 10^3$
	4C1	
	4C2	
	4D1	

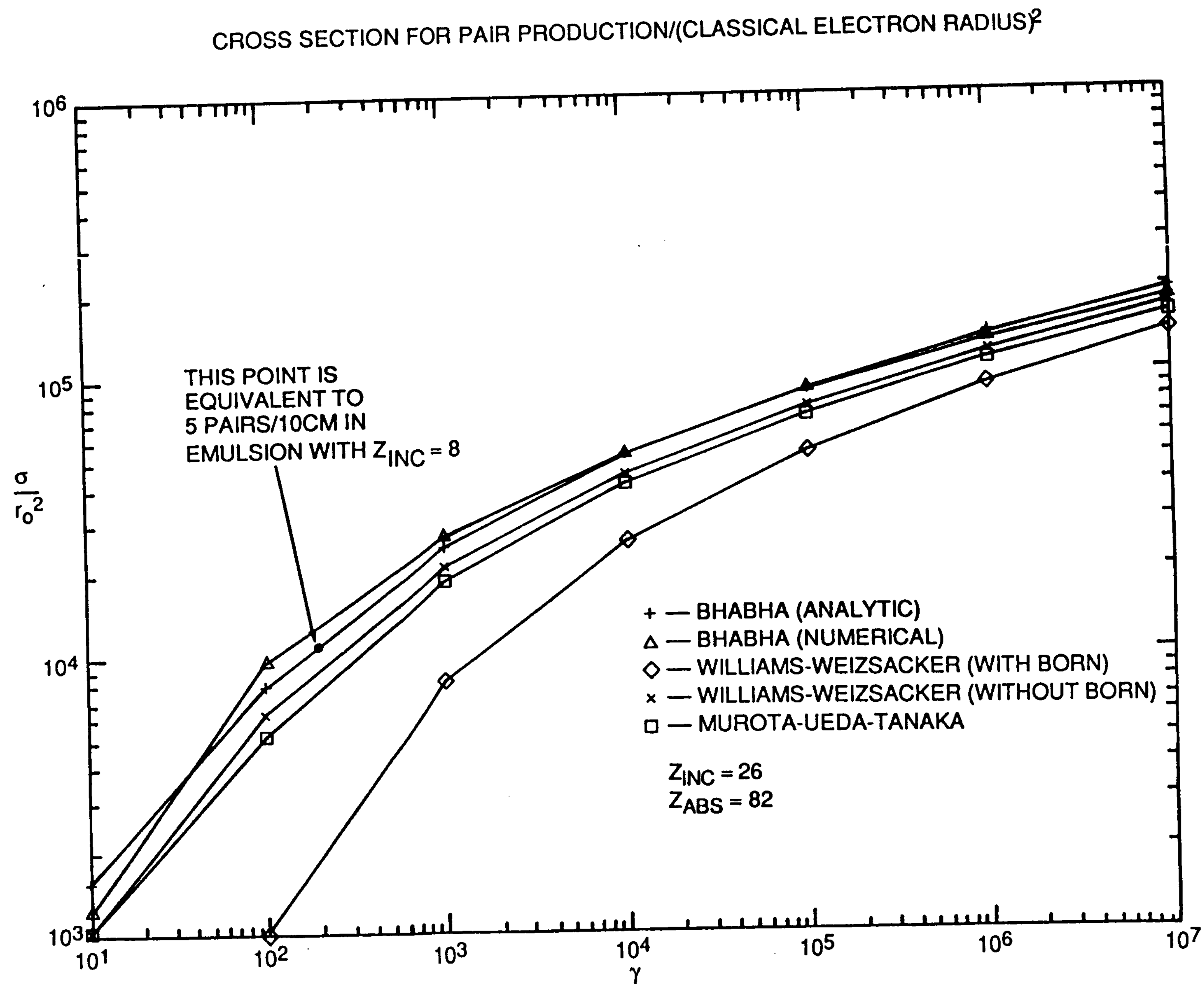
BEAM INTENSITY (60 GeV)

EXPERIMENT	CHAMBER	FLUENCE/cm^2
EMU04		
	4A3	
	4A4	
	4B3	
	4B4	$\sim 2 \times 10^3$
	4C3	
	4C4	
	4D3	$(2-3) \times 10^3$



1000
100
10
1
N_{PAIRS}/3cm EMULSION
10^1
10^2
10^3
10^4
10^5
10^6
10^7
LORENTZ FACTOR (γ)
MUT (NS) (1956)
MUT (S) (1956)
KOKOULIN-PETRUKHIN (1969)
TRIDENTS ADJUSTED TO 3 cm Fe (KOSHIBA & KAPLON, NAUGLE & FRIER)
O^{16} 200 GeV/AMU, PRELIMINARY
Fe^{56} 2 GeV/AMU PRELIMINARY
GRIGOROV et.al, CR NUCLEI
BUTT & KING, PROTONS

Figure 1 A



CROSS SECTION FOR PAIR PRODUCTION/(CLASSICAL ELECTRON RADIUS)^2
$\frac{\sigma}{r_o^2}$
10^6
10^5
10^4
10^3
10^1
10^2
10^3
10^4
10^5
10^6
10^7
γ
THIS POINT IS EQUIVALENT TO 5 PAIRS/10CM IN EMULSION WITH $Z_{INC} = 8$
+ — BHABHA (ANALYTIC)
Δ — BHABHA (NUMERICAL)
◇ — WILLIAMS-WEIZSACKER (WITH BORN)
× — WILLIAMS-WEIZSACKER (WITHOUT BORN)
□ — MUROTA-UEDA-TANAKA
$Z_{INC} = 26$
$Z_{ABS} = 82$

Figure 1B

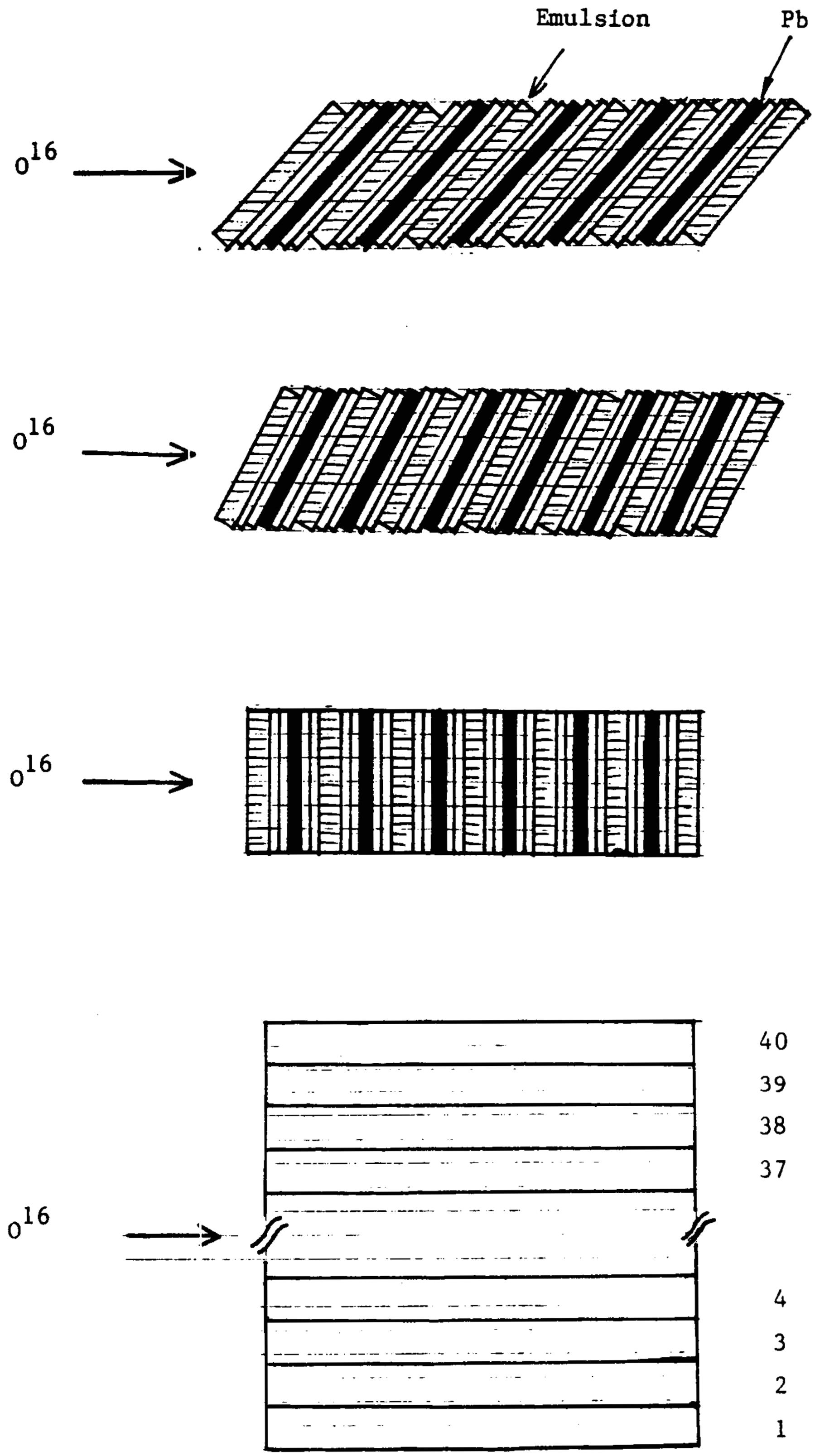


Figure 2. Emulsion Stacks for the CERN Experiments

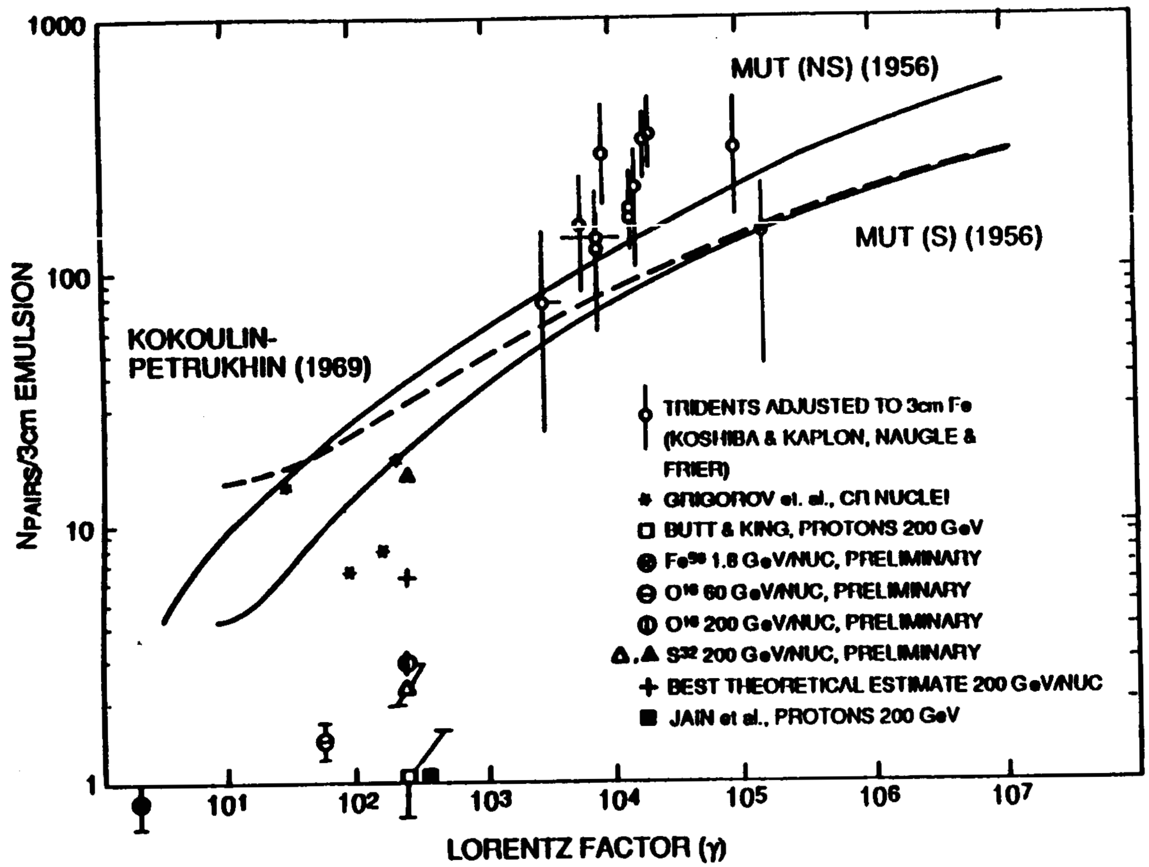
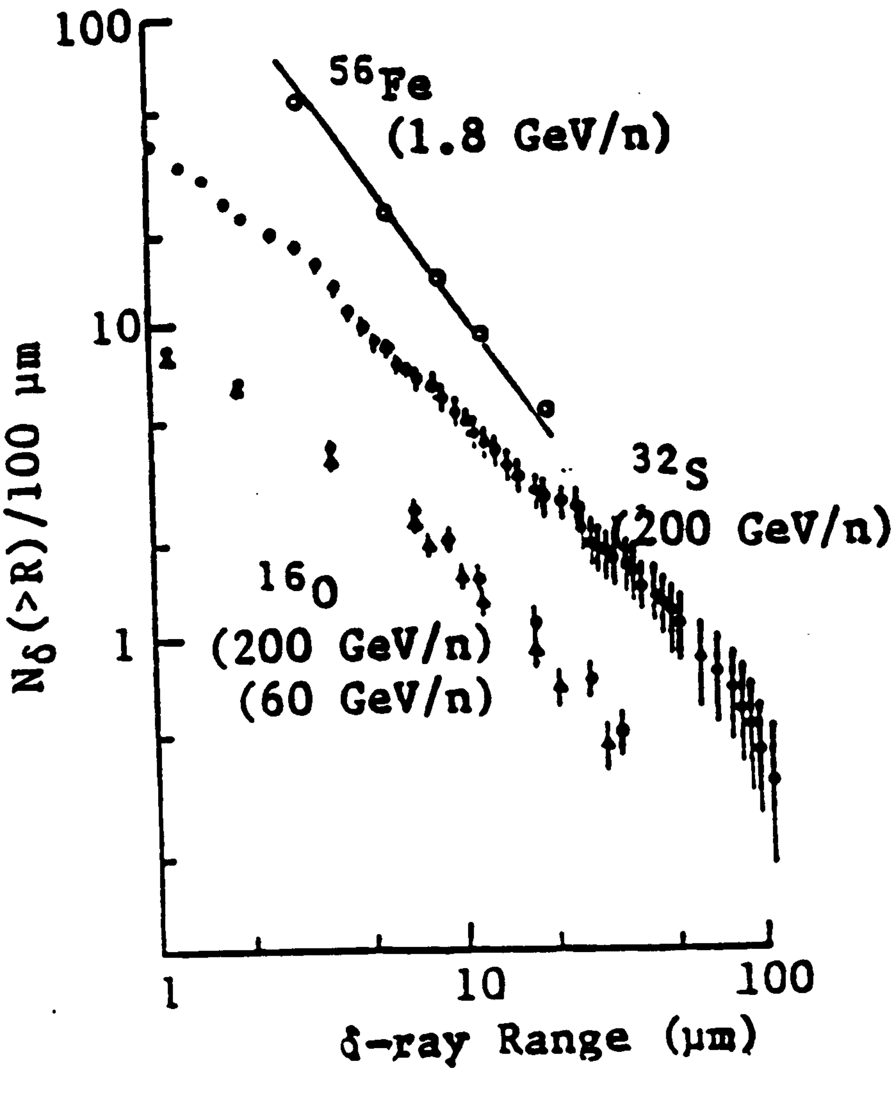


Figure 3. The yield of direct electron pairs produced in nuclear track emulsion by various primary projectiles (electrons, protons, oxygen, sulfur, iron) and several cosmic ray nuclei. The yields have been normalized to the equivalent yield of an Fe nucleus in 3 cm of emulsion.

Fig.4


100
10
1
^{56}Fe
(1.8 GeV/n)
^{32}S
(200 GeV/n)
^{16}O
(200 GeV/n)
(60 GeV/n)
$N_\delta(>R)/100\ \mu m$
1
10
100
δ-ray Range (μm)